Persistent Sub-yearly Chromospheric Variations in Lower Main-Sequence Stars: τ Boö and α Com [1]

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Photoelectric Observations of Variable Stars for Students

During the reporting period, we have worked with three students on student research projects: Davesh Maulik, Cristina Cristian, and Lynne Raschke.

Mr. Maulik's participation in our research program in the summer of 1996 was provided by MIT's Research Summer Institute. Mr. Maulik found unusual chromospheric variability in one of the recently-reported sunlike stars with exo-planets, Tau Bootes. The star shows a small-amplitude variability, that persists for the 30 years of its chromospheric record of observations, which has no explanation or counterpart in solar variability. He then searched the Mount Wilson data base for other examples of such variability in stars of similar mass, and found one other example. We are preparing a manuscript for publication in The Astrophysical Journal; a copy of the current version of the manuscript is attached.

In the Spring of 1997 Mr. Maulik won 4th place in the Westinghouse Science Competition.

Ms. Cristian, a Harvard undergraduate Physics major has been working with us part-time since September, 1996. Over the last several months, Ms. Cristian's primary duty has been in to reduce spectrophotometric data taken with the 60-inch and 100-inch telescopes at Mount Wilson Observatory as part of the "HK Project", a long-term effort to monitor the chromospheric activity of several hundred stars similar to the Sun. Specifically, she has been bringing the database up through the end of 1996, and most recently has been checking the database of over 300,000 observations for low-quality observations.

In addition to this task, Ms. Cristian has also helped prepare a target list for two star clusters: Melotte 22 (the Alpha Persei cluster) and Messier 45 (the Pleiades). Both clusters are young (with ages of 50 and 75 million years, respectively). These stars will be observed with the 100-inch telescope to extend the chromospheric age/activity /rotation relationship to younger stars. One effect of this revised calibration will be to further examine the stellar birth rate in the solar neighborhood.

Over the next few months, we will be calibrating the HK database to prepare the archive for future analysis. Several scientific initiatives relying upon the HK database will benefit from these data when they are fully analyzed and become available. This will require substantial effort in analyzing the standard lamp and standard stars, which provide the basis for our calibration. This effort is crucial for future high-school research programs because it brings the data base up to date for research.

Ms. Raschke is an undergraduate from Haverford who will be studying the evolution of angular momentum and activity cycles in post-main sequence stars in the Mount Wilson data base. Her funding will be provided by the Smithsonian Astrophysical Observatory's Summer Intern Program. Through this cooperative effort she will be preparing our data base of evolved stars for future work with high-school students.

ABSTRACT

The recent discoveries of extrasolar planetary systems around lower main-sequence stars such as τ Boö (HD 120136) has prompted further investigation into their stellar activity. A cursory analysis of τ Boö for cyclic chromospheric activity, based on its 30-yr record of Ca II H and K fluxes obtained as part of the HK Project from Mount Wilson Observatory, finds an intermediate, sub-yearly period ($\sim$ 117 d) in chromospheric activity in addition to, and separate from, both its rotation (3.3 d) and long-term variability. As a persistent subyearly period in surface magnetic activity is unprecedented, we investigate this apparent anomaly further by examining chromospheric activity levels of other stars with similar mass, searching for variability in chromospheric activity with periods of less than one year, but longer than measured or predicted rotation.

An examination of the time series of 40 mid-to-late F dwarfs yielded one other star for further analysis: α Com (HD 114378, P $\sim$ 132 d). The variations for these two stars were checked for persistence and coherence. Based on these determinations, we eliminate the possibilities of rotation, long-term activity cycle, and the evolution of active regions as the cause of this variation in both stars. In particular, for τ Boö we infer that the phenomenon may be chromospheric in origin; however, beyond this, it is difficult to identify anything further regarding the cause of the activity variations, or even whether the observed modulation in the two stars have the same origin.

1. Introduction

Through highly precise radial velocity measurements, the process of identifying extrasolar planetary systems around lower main-sequence stars has begun (Mayor & Queloz 1995; Butler & Marcy 1996; Marcy & Butler 1996; Butler et al. 1997). In the case of τ Boö (HD 120136, F7V), radial velocity measurements indicate a planet with a minimum mass of 3.87 M_J in a circular orbit 0.0462 AU from the star (Butler et al. 1997), an orbit much closer than Mercury's orbit around the Sun. Because of the increased attention devoted to these new systems, long-term measurements of stellar activity (chromospheric and otherwise) have also merited increased discussion (Henry et al. 1997). In the course of closer examination of Ca II flux measurements for τ Boö from Mount Wilson Observatory, an unusual period of 117 days was detected. Variability in the chromospheric records for this star at this particular time scale was noted before (Dobson et al. 1990) but was ascribed to active region growth and decay. Persistent cycles in stellar activity of this subyearly length are not present in lower, main-sequence stars or the Sun. Furthermore, analysis of stellar data typically avoids this time scale because it is not associated with conventional periods (rotation, activity cycles) and because such analysis is complicated by the presence of yearly gaps in observations. However, in this case, the period cannot be as easily dismissed because it is not associated with the effect of seasonal gaps uneven sampling in the records of τ Boö. Consequently, the strange period appearing in τ Boö is worthy of further analysis, not only of the star itself but of other stars of similar spectral type in order to verify its appearance, find other instances of occurrence, and to characterize its nature.

2. Observations

In an effort to monitor long-term chromospheric activity variations similar to the Sun's 11–year sunspot cycle (Schwabe 1843; Wolf 1856), approximately 100 main-sequence stars have been observed since 1966 from Mount Wilson Observatory's 100-inch telescope at roughly monthly intervals (Wilson 1978; Baliunas et al. 1995). More frequent monitoring of these stars began on the Observatory's 60-inch telescope in 1980, and observations are made on roughly 300 nights every year. Each yearly observing season is 150 – 200 days in length. Of the 111 main-sequence stars with long-term observations (Baliunas et al. 1995), 40 are mid-to-late F dwarfs, including τ Boö (F7 V).

Stellar chromospheric activity was measured from variations in the emission flux of Ca II H (369.8 nm) and K (393.4 nm) lines of the stellar spectra. In lower main-sequence stars, the intensity of the emission of these lines varies with changes in heating from local magnetic phenomena analogous to sunspots, plages, and occasionally flares. In the spectrophotometer used to measure the emission fluxes, a chopper wheel measures the flux results simultaneously in four channels at a frequency of 30 Hz. Two of these channels are 0.109 nm wide centered on the Ca II H and K lines while the other two are channels 2.0 nm wide centered on 389.1 nm and 400.1 nm (labeled V and R). The recorded quantity, the S index, is the ratio of the H and K fluxes to the V and R continuum fluxes, i.e., $S = \alpha(H + K)/(V + R)$, where α is a nightly calibration factor determined by observing presumably invariant standard stars and a standard lamp.

Three sequential observations are made for each star per night, continuing until a preset count (usually greater than 2000) in the K channel is met for each observation. Finally, background readings are taken throughout the night and subtracted from each channel's counts. The overall precision of the instrument and subsequent calibration is 1.0–1.5% (Baliunas et al. 1995), based on the least variable stars.

3. Analysis

Power spectra of the unevenly-sampled time series (Scargle 1982; Horne & Baliunas 1986) are used to detect variability. Such analysis has the advantage of providing an estimate of the validity of the highest peak in the periodogram, the false alarm probability (FAP). The FAP represents the probability that a peak of certain height would occur assuming the data are *purely* Gaussian noise. In considering the stellar data, this FAP is compromised by the fact that the noise is definitely *not*

Gaussian in nature; for example, the noise generated by the growth and decay of active regions is not Gaussian (but is astrophysical signal).

As a first test, we limited the search range of periods to 50 – 1000 days. Variability at time scales beyond this range in either direction would likely have been detected by previous searches for rotation and activity cycle periods (Baliunas et al. 1995). We limited consideration to F-class stars like τ Boö; the list of candidate stars appears in Table 1. For each star, we searched for persistent peaks in the periodogram of the longest records (30 yr) whose amplitude was apparent in the star's time series and whose frequency was not likely to be associated with peaks in the window function. The possibility exists that stars examined in this manner may vary with a period within the search interval but may be infortuitously close to peaks arising from the window function to be detectable. Furthermore, the FAP cannot be considered too literally as an absolute measure of confidence; therefore, both a high FAP and a visible amplitude were prerequisites for selecting a star for further analysis.

From this search for variability similar to τ Boö, one additional star was found: α Com (HD 114378) with a 132-day period. We subsequently analyzed each star's time series for consistency of period and amplitude over shorter intervals. To do this, we limited our analysis to data taken following 9 June 1980, after which time observations were scheduled several times per week throughout each observing season; the intervals before this time lack sufficient data coverage for in-depth analysis. The intervals used comprised of three sequential seasons taken together in order to provide for sufficient cycles per interval. This choice of interval, however, complicates the analysis since it introduces spectral leakage by way of the seasonal gap. In focusing on the intermediate time-scale variation for each star, any long-term modulation of the star's Ca II flux interferes with periodogram analysis, particularly in calculation of the amplitude, as periodogram analysis attempts to fit the varying data at each frequency tested using sinusoidal curves in which amplitude is held constant over the interval tested. In order to eliminate this impact, long-term variations were removed from the data by breaking down trends into linear components and removing each component separately. These components were identified visually, i.e., if seasonal data appeared to increase at a reasonably constant rate over a length of time, this length was considered a component.

3.1. τ Boötis

In order to reduce the effects of long-term variability to the data, a spline fit to seasonal means was subtracted from the data. The periodogram of this adjusted data produced a period of 116.686 days and semi-amplitude of 0.00236 (in S units). A periodogram was calculated over each interval (thus the need for 3 seasons at a time). The resultant periods and amplitudes are shown in Table 2. For these periodograms, the range of frequencies tested was restricted from 0.006 day^{-1} to 0.010 day^{-1} since the strength and variability of the one intermediate period was all we wished to gauge. Two consecutive seasons in the data, years 1990 and 1991, were poorly sampled and, consequently, there are few firm detections of variability near this epoch.

(Need to redo the following paragraph)

Ideally, we would have preferred an indication of to what extent the data in each interval stays in phase over the period, as this can be an indication of the growth and decay of active regions as a cause. However, this was not possible through a phase plot as slight fluctuations in the period lead to significant variations in the phase curve. This is not a problem, fortunately, as the relative coherency of the period precludes a connection to the growth-and-decay phenomenon (see below). For our purposes, the phase curve over the entire time series suffices.

3.2. α Com

The analysis of the 132-day period present in the activity of α Com was the same as that of the period of τ Boö. As before, linear trends in the data were removed from the long-term trend to minimize their interference; in this case, the long-term activity was divided into four such trends. The periodogram for the adjusted data yielded a period of 131.926 days with a semi-amplitude of

0.0026; the resulting fitted sinusoid is $y = 0.0026\cos(\frac{2\pi(t-0.654)}{131.926})$. This fit was compared to the entire data set and single intervals, again calculating the rms with the periodogram. The results for α Com are listed in Table 3. As before, data collected during 1990 and 1991 were poorly sampled and results for these intervals were discarded.

4. Discussion

Based on our analysis of τ Boö and α Com, subyearly variations persist in the Ca II time series of these stars over at least 15 years. The periods do not correspond to known variations in solar activity. Nonetheless, we should consider possible explanations for the appearence of these periods.

4.1. Rotation

Rotation periods have been derived for a several dozen lower main sequence stars (Baliunas et al. 1983) and evolved stars (Choi et al. 1995), and long-term observations of rotation suggest that it is also possible to detect the presence of surface differential rotation (Baliunas et al. 1985; Donahue 1993).

The 117-day and 132-day variations observed appear similar to the rotational modulation of evolved stars (Choi et al. 1995). However, those stars are later than spectral type G0 III where significant loss of angular momentum takes place (e.g., Simon 1984).

A possible rotation period in the range of 3.3 ± 0.5 days has been detected by Baliunas et al. (1997). Similarly, the measured rotation period for α Com is 3.0 ± 0.2 days (Donahue 1993). These periods agree with those expected for F dwarf stars of intermediate age (Noyes et al. 1984). Furthermore, the projected rotational velocities measured for these stars, $v \sin i = 14.8 \pm 0.3$ km s^{-1} for τ Boö (Gray 1982), and $v \sin i = 21.3 \pm 1.0$ km s^{-1} for α Com (Soderblom, Pendleton, & Pallavicini 1989) are consistent with the reported 3-day rotation periods and preclude rotation periods on the order of 100 days.

4.2. Activity Cycles

Both stars were analyzed by Baliunas et al. (1995) for the presence of long-term activity variations. A weak cycle of 11.6 ± 0.5 yr was found for τ Boö, and only a long-term trend was seen for α Com. Although cycle periods as small as 2 years have been reported in the Wilson sample, stars with persistent cyclic activity tend to have periods longer than 7 years. Individual sunspot cycle lengths from 7 to 15 years (Donahue & Baliunas 1992), and individual cycles vary greatly in amplitude.

(We need to look at the persistence of AMPLITUDE too!!!)

4.3. Active Region Growth and Decay

Magnetic surface inhomogeneities evolve on the stellar surface with time. Their formation, growth, and decay are seen in long-term measurements as a roughly cyclical effect. On the Sun, new active regions tend to develop near previous centers of activity. Therefore, these "active longitudes" could create a pattern that is somewhat cyclic, even if not strictly periodic. The timescale for active region evolution for large complexes matches the periods of the variations seen (Donahue, Dobson, & Baliunas 1996). As mentioned earlier, growth and decay was initially posited (Dobson et al. 1990) to be the cause of the intra-seasonal variation observed for τ Boö.

However, active region evolution is not periodic, and significant development within an active region complex can occur making the overall envelope of activity non-sinusoidal in character. Furthermore, if growth and decay were the cause of the 100-day periodicites, we would expect a greater amplitude of rotational modulation with a greater number of active regions, i.e. with a greater average flux. However, the rms over the course of the intervals is reasonably constant and, while the amplitude of the cycle does fluctuate, these fluctuations do not correspond to rises in the general activity of the star. With α Com, while there are more significant variations in rms and amplitude, the persistence of the period and the coherency of the phase once again suggest that this is not simply a growth-and-decay phenomenon. However, as the period only becomes strong after the first few seasons, after which it is quite persistent, this question is far from resolved.

4.4. Comparison with Other Time Series

Precise radial velocity readings for τ Boö, (Marcy 1996, private communication), do not show variability on the order of 100 – 200 days. However, the basis for this conclusion is weak as the star has been sampled intermittently over the past nine years and heavily only over the past three months, placing a 100-day period, mostly beyond scrutiny. If such a variation is present in the radial velocity data at the periods seen in the Ca II fluxes, it would suggest that the subyearly variation arise from something related to the presence of a close companion. On the other hand, well-sampled photometric measurements (Baliunas et al. 1997) show no periodic changes over this timescale for τ Boö. This suggests that the period for τ Boö is solely chromospheric in origin with no further component of variability. As of this writing, the corresponding spectroscopic and photometric analyses have not been performed for α Com.

Further discussion over possible causes is pure speculation. For τ Boö, it is plausible that the existence of a massive planet within close proximity could influence chromospheric surface; the planetary revolution period similar to the stellar rotation period is a possible indication of interaction between the two. However, why such a disturbance would occur on a 116-day timescale and not on the 3-day revolution timescale is unclear.

We are indebted to past and present members of the HK Project, without whom the long-term Ca II H and K database would not exist. Many thanks go to Lou Boyd for operating and maintaining the Fairborn APT site. Automated astronomy at TSU has been supported for several years by the National Aeronautics and Space Administration and by the National Science Foundation, most recently through NASA grants NAG 8–1014, NCC2–883, and NCCW–0085, and NSF grant HRD–9550561. This project was supported by the MIT Space Grant Consortium, and the MIT RSI Program operated by the Center of Excellence in Education. Research for the HK Project was supported by the Scholarly Studies Program, and the Langley-Abbot Program of the Smithsonian Institution, the Center of Excellence in Information Systems of Tennessee State University, the Richard Lounsbery Foundation, and the Mobil Foundation, Inc., as well as several generous individuals.

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Table 1. F-class Stars from Wilson's Sample

HD	$B-V$	Spectral	$\langle S \rangle$	$-\log R_{HK}$
2454	0.43	F2V	0.170	4.792
3229	0.44	F2V	0.224	4.583
6920	0.60	F8V	0.194	4.793
13421	0.56	F8V	0.131	5.195
16673	0.52	F8V	0.215	4.664
18256	0.43	F5V	0.185	4.772
25998	0.46	F7V	0.300	4.401
33608	0.46	F6V	0.214	4.628
35296	0.53	F8V	0.332	4.378
45067	0.56	F8V	0.141	5.094
61421	0.42	F5IV-V	0.171	4.777
72905	0.62	F7V	0.367	4.375
75332	0.49	F7V	0.279	4.464
76572	0.43	F3V	0.148	4.924
88355	0.46	F6V	0.170	4.819
88737	0.56	F5V	0.234	4.622
89744	0.54	F6V	0.137	5.120
100180	0.57	F7V	0.165	4.922
100563	0.46	F5V	0.202	4.674
106516	0.46	F6V	0.208	4.651
107213	0.50	F8V	0.135	5.103
111456	0.46	F6V	0.300	4.402
114378	0.45	F5V+F5V	0.244	4.530
115383	0.58	F8V	0.313	4.443
120136	0.48	F7V	0.191	4.731
124570	0.54	F6V	0.133	5.156
124850	0.52	F7IV	0.210	4.682
136202	0.54	F8IV-V	0.140	5.088
142373	0.56	F9V	0.147	5.042
154417	0.57	F8V	0.269	4.533
157856	0.46	F5V	0.202	4.674
159332	0.48	F4V	0.144	5.006
176095	0.46	F5IV	0.202	4.671
182101	0.44	F6V	0.216	4.608
187013	0.47	F5V	0.154	4.922

Table 1—Continued

HD	$B-V$	Spectral	$\langle S \rangle$	$-\log R_{HK}$
187691	0.55	F8V	0.148	5.026
194012	0.51	F5V	0.198	4.720
207978	0.42	F0V	0.152	4.890
212754	0.52	F5V	0.140	5.073
216385	0.48	F7IV	0.142	5.025

Table 2. Interval Analysis of Adjusted Fluxes for HD 120136

Interval (seasons)	Number of Observations	Period $\pm\Delta P$ [days]	Semi-Amplitude (S-units)	Q	FAP (%)	rms (S)
1981–1995	2696	116.6 ± 0.1	0.0025	213	$< 10^{-11}$	0.0045
1981–1983	504	115.9 ± 0.9[a]	0.0023	31	9.5×10^{-10}	0.0042
1982–1984	807	118.2 ± 0.7	0.0025	51	$< 10^{-11}$	0.0048
1983–1985	850	111.9 ± 0.5	0.0033	93	$< 10^{-11}$	0.0051
1984–1986	1159	113.8 ± 0.3	0.0042	196	$< 10^{-11}$	0.0050
1985–1987	886	117.9 ± 0.3	0.0043	181	$< 10^{-11}$	0.0048
1986–1988	825	122.2 ± 0.4	0.0039	144	$< 10^{-11}$	0.0045
1987–1989	424	121.4 ± 1.1	0.0021	27	3.8×10^{-8}	0.0042
1988–1990	304	114.6 ± 1.3	0.0018	21	1.1×10^{-5}	0.0039
1989–1991	160	114.6 ± 1.5	0.0022	13	9.6×10^{-3}	0.0041
1990–1992	216	...	...	...	...	0.0036
1991–1993	304	...	...	...	...	0.0038
1992–1994	492	...	...	...	...	0.0038
1993–1995	392	118.2 ± 0.6	0.0035	58	$< 10^{-11}$	0.0042

[a]Period after filtering of another peak in the power spectrum

Table 3. Interval Analysis of Adjusted Fluxes for HD 114378

Interval (seasons)	Number of Observations	Period $\pm\Delta P$ [days]	Semi-Amplitude (S-units)	Q	FAP(%) (%)	rms (S)
1981–1995	2134	126.1 ± 0.1[a]	0.0024	113	$< 10^{-11}$	0.0053
1981–1983	401	135.0 ± 2.0	0.0016	19	9.1×10^{-5}	0.0040
1982–1984	410	88.3 ± 0.7[b]	0.0019	28	5.9×10^{-9}	0.0043
1983–1985	526	174.5 ± 2.2	0.0022	33	7.8×10^{-11}	0.0046
		93.8 ± 0.6[c]	0.0021	32	3.4×10^{-10}	
1984–1986	608	181.5 ± 1.6	0.0029	65	$< 10^{-11}$	0.0048
		98.6 ± 0.6[c]	0.0020	34	2.5×10^{-11}	
1985–1987	621	126.3 ± 0.7	0.0036	77	$< 10^{-11}$	0.0051
1986–1988	578	131.8 ± 0.6	0.0038	83	$< 10^{-11}$	0.0050
1987–1989	448	134.8 ± 1.1	0.0030	43	$< 10^{-11}$	0.0050
1988–1990	352	129.0 ± 1.8[a]	0.0017	13	4.0×10^{-2}	0.0045
1989–1991	177	...	...	...	...	0.0043
1990–1992	255	...	...	...	...	0.0056
1991–1993	342	129.0 ± 0.6	0.0054	75	$< 10^{-11}$	0.0056
1992–1994	530	136.0 ± 0.4	0.0064	156	$< 10^{-11}$	0.0062
1993–1995	419	128.9 ± 0.7[a]	0.0048	68	$< 10^{-11}$	0.0070

[a]Period after filtering of another peak in the power spectrum

[b]Single strong peak

[c]Period after filtering of previously listead peak